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Summary of Beam-beam Observations during Stores in RHIC[1]

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Abstract. During stores, the beam-beam interaction has a significant impact on the beam and luminosity lifetimes in RHIC. This was observed in heavy ion, and even more pronounced in proton collisions. Observations include measurements of beam-beam induced tune shifts, lifetime and emittance growth measurements with and without beam-beam interaction, and background rates as a function of tunes. In addition, RHIC is currently the only hadron collider in which strong-strong beam-beam effects can be seen. Coherent beam-beam modes were observed, and suppressed by tune changes. In this article we summarize the most important beam-beam observations made during stores so far.

INTRODUCTION

The beam-beam interaction is a major consideration in the operation of RHIC. It can lead to emittance growth and particle loss, and is a source for experimental background. Machine parameters, close to the maximum parameters achieved so far, are presented in Tab. 1, a full parameter list can be found in Ref. [1].

RHIC consists of two superconducting rings, Blue and Yellow, and has produced gold-gold, proton-proton and deuteron-gold collisions [2]. With RHIC's interaction region design (see Fig. 1) and with 4 experiments most bunches experience 4 head-on, and 2 long-range collisions per turn. However, due to the abort gaps, some bunches experience only 3, and some only 2 head-on collisions. The long-range interactions are with at least 7 rms beams sizes separation. With 120 or less bunches per ring (the current limit), sets of 3 bunches in one ring and 3 bunches in the other ring are coupled through the beam-beam interaction (see Ref. [3]).

Even small tune shifts due to the beam-beam interaction can be observed directly with a high precision tune measurement system [4]. In Fig. 2 a tune shift measurement is shown that was taken 3 hours into a gold-gold store.

Two beam splitting DX dipoles are the magnets closest to the interaction point (IP). They are each 10 m away from the IP (see Fig. 1). Beams collide nominally without a crossing angle. With rf manipulations, the crossing point can be moved longitudinally. If the bunch spacing is large enough (with 60 or less bunches per ring), it is possible to separate the beams longitudinally and switch off all 6 beam-beam interactions. If the crossing point is moved within the DX magnets, an observed tune shift is a sign of crossing angles (Figs. 1 and 2). The sum of all residual crossing angles is typically about 0.5 mrad.

Beam-beam phenomena observed in other hadron colliders [5] can also be seen in RHIC [6]. In addition, with bunches of equal intensity the beams are subject to strong-strong effects. To accommodate acceleration of different species, the two RHIC rings have independent rf systems. With different rf frequencies the beam-beam interaction is modulated and can have a visible impact on the beam lifetime [7].

TABLE 1. Machine parameters relevant to beam-beam interactions, for Au-Au and p-p collisions. The beam-beam parameters in deuteron-gold collisions are close to those in gold-gold collisions.

parameter	unit	Au-Au	p-p
relativistic γ, injection	...	10.5	25.9
relativistic γ, store	...	107.4	106.6
no of bunches n_b	...	55	55
ions per bunch N_b	10^9	1	100
emittance $\varepsilon_{Nx,y95\%}$	μm	10	20
chromaticities (ξ_x, ξ_y)	...	(+2,+2)	
harmonic no. h, store	...	7×360	360
synchrotron tune Q_s	10^{-3}	3.0	0.5
rms bunch length σ_z	m	0.3	0.7
rms momentum spread σ_p/p	10^{-3}	0.15	0.3
envelope function at IP β^*	m	1–10	
beam-beam ξ/IP	...	0.0023	0.0037
crossing angle θ	mrad	0.0	
head-on collisions	...	2–4	
parasitic collisions	...	4–2	

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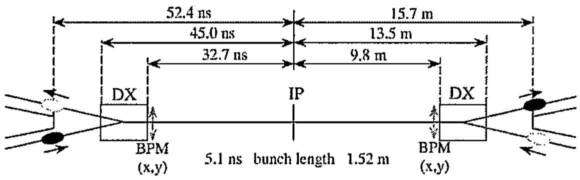

FIGURE 1. RHIC interaction region. Beams share a common beam pipe between the beam splitting DX dipoles. The bunch spacing shown corresponds to a fill pattern of 120 symmetrically distributed bunches.

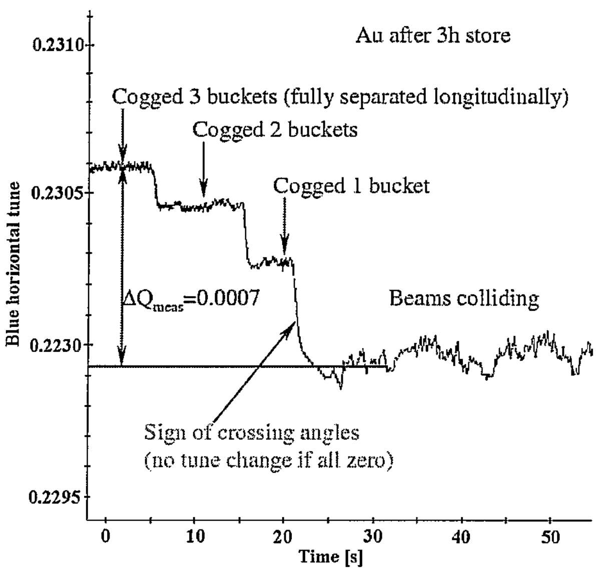

FIGURE 2. Tune as a function of longitudinal beam crossing position. Cogging by one acceleration bucket moves the crossing point by 5 m.

The beam-beam tune shift depends on the bunch intensity and emittance. Since the bunch intensities can be measured with good precision, the beam-beam tune shift measurement also provides an emittance estimate.

LIFETIME AND EMITTANCE GROWTH

The beam-beam interaction is most pronounced for proton-proton collisions with larger β^* values (Tab. 1). In lattices with small β^* uncorrected nonlinear field errors in the triplets have a significant impact on the beam lifetime. Fig. 3 shows the distributions of the bunched beam lifetimes for polarized proton collisions during the 2001 run, with $\beta^* = 3$ m at all IPs. The distributions are relatively wide with a mean of about 15 hours. The average bunch intensity for all stores in the plot is $N_b = 0.4 \cdot 10^{11}$ with an 95% normalized emittance of $\varepsilon_N = 25$ μm, corresponding to a beam-beam parameter of $\xi = 0.0015$/IP. Gold beam lifetimes are generally lower due to intra-

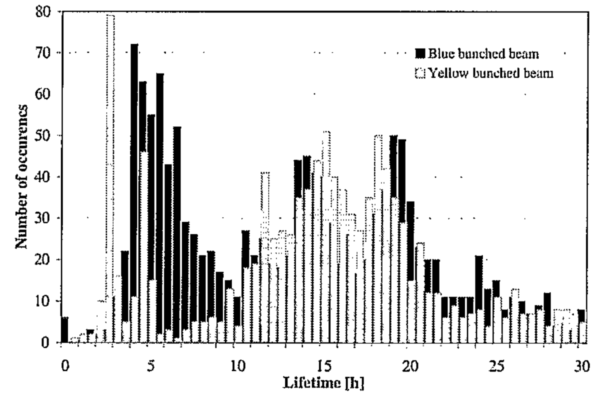

FIGURE 3. Blue and Yellow bunched beam lifetimes with proton-proton collision during one month of operation.

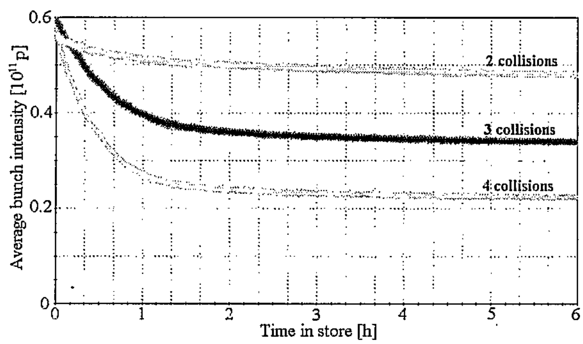

FIGURE 4. Average bunch intensity of 5 bunches each with 2, 3 and 4 head-on collision respectively during a proton store. The initial beam-beam parameter is $\xi = 0.002$/IP.

beam scattering. A deuteron beam without collisions, in a lattice with $\beta^* = 2 - 10$ m, provides a good comparison to see the impact of the beam-beam interaction. Its lifetime is only marginally influenced by intra-beam scattering or nonlinear triplet errors. 55 bunches with $N_b = 0.5 \cdot 10^{11}$, stored for an hour, showed a lifetime of 830 h.

From the change in the beam intensity and the observed luminosity an estimate for the emittance growth can be obtained, assuming the same emittance in both beams. For proton-proton collisions we find $\Delta\varepsilon/\varepsilon = 4\%$ in the first store hour (with an rms value of 5%). For comparison, no emittance growth was observed with the ionization profile monitor in the deuteron beam measurement without beam-beam interaction.

While most bunches experience 4 head-on collisions, some bunches experience only 3 or 2 head-on collisions. In proton-proton collisions, these have visibly larger beam lifetimes (see Fig. 4). For this reason, beams were only collided in two experiments in the latter part of the last proton run.

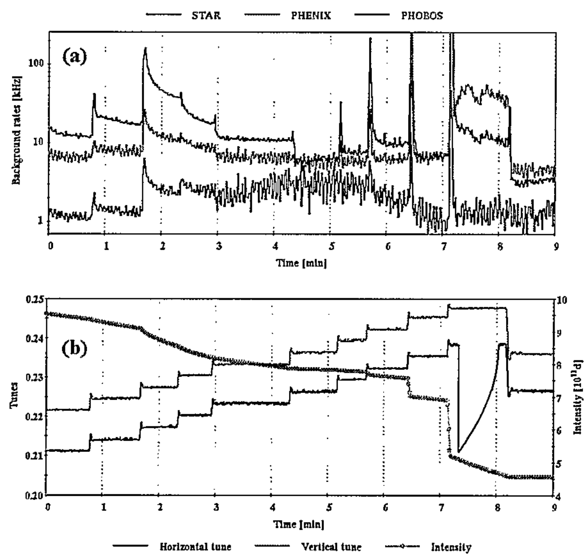

FIGURE 5. (a) Experimental background rates during a working point scan. (b) Deuteron beam intensity and transverse tunes during the scan.

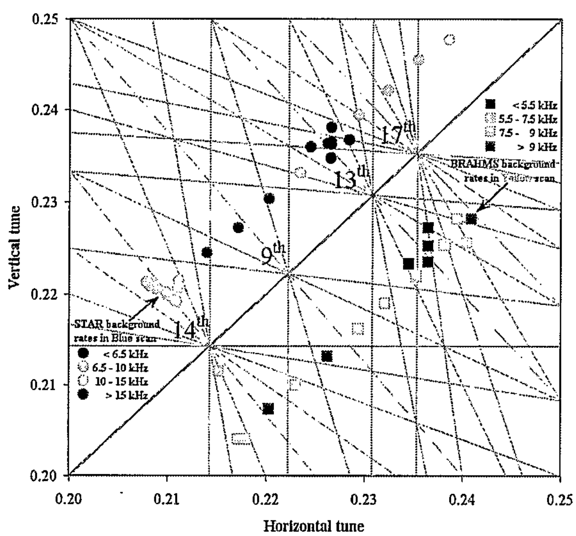

FIGURE 6. Experimental background rates as a function of fractional coherent tunes. For these measurements deuterons in the Blue ring collide with gold ions in the Yellow ring. The total beam-beam tune spread due to the beam-beam interaction is about $\Delta Q_{tot} = 0.005$ in both measurements.

WORKING POINT AND BACKGROUND

Both transverse RHIC fractional tunes (Q_x, Q_y) are kept between 0.2 and 0.25, and during stores close to the coupling resonance $Q_x = Q_y$. In this area the lowest order resonances are of order 9, 13, 14 and 17 (see Fig. 6). If the nonlinear dynamics are dominated by the beam-beam

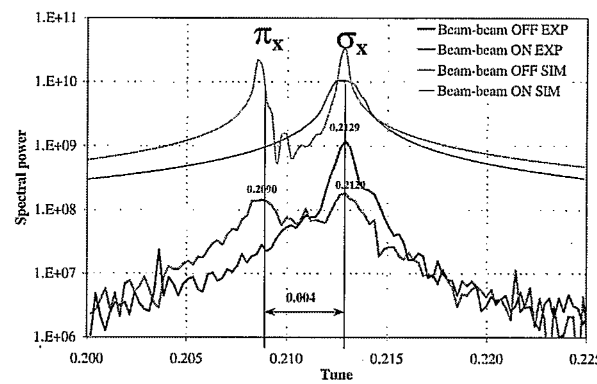

FIGURE 7. Coherent dipole modes in an experiment with a single proton bunch per beam, and in a corresponding simulation [12]. $\xi = 0.003$, spectra from 4096 turns.

interaction and the crossing angles are all zero, no odd-order resonances are driven.

Experimental background rates were observed as a function of the tunes with deuteron-gold collisions (see Figs. 5 and Fig. 6), and proton-proton collisions. The tunes were moved parallel to the $Q_x = Q_y$ line, scanning the area considered for operation. With both beams, high background rates were found near 9^{th} order resonances, and low background rates near 13^{th} order resonances. The working points with low background rates are used in operation. High background rates near 9^{th} order resonances are another sign of residual crossing angles (cf. Fig. 2). Increased background rates were also found with a transverse offset [8].

STRONG-STRONG OBSERVATIONS

RHIC sees strong-strong beam-beam effects. In addition to the tune (σ-mode) a new transverse oscillation mode (π-mode) occurs. For a single collision per turn the π-mode is at a tune $Y\xi$ below the σ-mode, where $Y \approx 1.2$ for round beams [9]. If the beam-beam interaction is the dominant nonlinear effect, the π-mode can be outside the continuous spectrum and thus be undamped [10].

Coherent beam-beam modes were observed in an experiment with proton beams, with a beam-beam parameter $\xi = 0.003$ and a single collision per turn (see Fig. 7). The measured difference between the σ- and π-modes is consistent with a Yokoya factor of $Y \approx 1.2$. The locations of the π-modes were reproduced in a strong-strong simulation [12]. π-modes were also observed in routine operation with a beam-beam parameter $\xi = 0.0015$, four collisions per turn and linear coupling (see Fig. 8). The π-modes could be suppressed by small changes in one of the tunes (see Fig. 8).

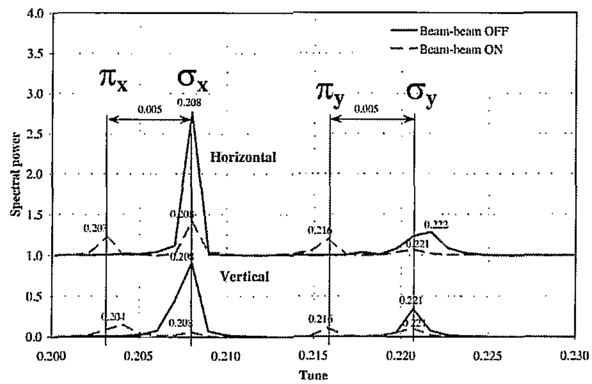

FIGURE 8. Coherent dipoles modes in operation with 4 collisions per turn. $\xi = 0.0015$/IP, spectra from 1024 turns.

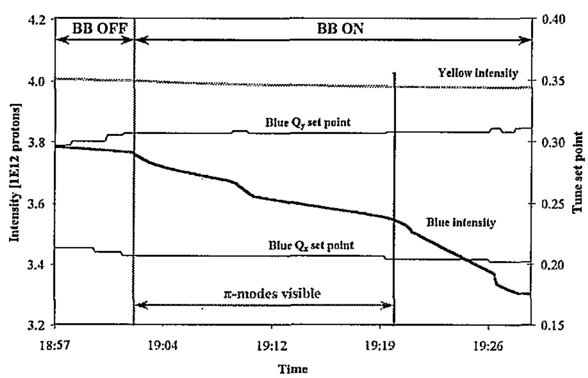

FIGURE 9. Blue and Yellow beam intensity and Blue tune set points during tuning for lifetime at the beginning of a proton store. π-modes were only visible for certain tune set points.

SUMMARY

The beam-beam interaction has a significant impact on lifetime and emittance of the RHIC beams, as well as the experimental background. In addition to beam-beam effects observed in other hadron colliders, coherent beam-beam modes were seen for the first time. So far, coherent modes could be suppressed by small tune changes.

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